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AN ASSESSMENT OF SECONDARY LOSS REDUCTION TECHNIQUES
FOR STME LOX TURBINE

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One of the primary objectives of the National Launch System (NLS) program, explored jointly by NASA and several other government agencies, is to develop a new Space Transportation Main Engine (STME) which will perform better and is more reliable than the present Space Shuttle Main Engine (SSME). Preliminary design of the Oxidizer (LOX) turbine in STME has recently been completed by Pratt and Whitney (P&W). It is a single-stage, highly impulsive turbine with an approximately 170-degree deflection angle across the rotor. Due mainly to strong flow turning, the secondary loss in the rotor passage accounts for nearly 50% of the total loss over the entire stage, based on a mean-line prediction reported by P&W. To reduce such a significant loss with an aim to further improve STME performance has recently become one of the major research tasks for the Consortium Turbine Team at MSFC. As part of this team effort, the primary objective of the present study is to identify and examine prospective approaches for secondary loss reduction. Relevant information reported earlier in the open literature, primarily for jet-engine applications, has also been reviewed to a great extent. It is hoped that information gained from this study will promote further understanding toward these approaches and their potential applicability in STME turbines.

SECONDARY LOSS

The secondary loss is due to energy dissipation induced by the secondary flow in a blade passage. By definition, secondary flow is a recapitulation of flow motions which are deviated from the primary flow pattern in the passage. In classical turbine flow dynamics, the primary flow is governed by the potential theory, and it is two-dimensional in nature. The secondary flow in a turbine passage consists of two fundamental modes. The first mode is similar to the Dean-type flow motion existing in curve ducts and rotating channels. The velocity differential between the pressure side and suction side of a blade passage, which further induces non-uniform vortex stretching in the streamwise direction, is responsible for this phenomenon. Details of cascade flowfield in this respect have been extensively investigated in recent years as reported by Sieverding (1985).

The second mode, as a result of endwall-blade interaction, is initiated by a three-dimensional flow separation occurred upstream to the blade stage. This flow mode inherits more complex motion and is considered to be more accountable for the overall secondary loss, especially for blades with low aspect ratios. Figure 1 reveals a schematic sketch of cascade endwall flow structure given earlier by Sharma and Butler (1987). The separation occurred upstream forces boundary layer to roll-up and forming a flow structure similar to the well-known horseshoe vortex. Further downstream, the vortex splits into two legs, normally termed the pressure and the suction side legs, and they then enter the passage in a counter-rotating fashion and interact strongly with the mainstream. Immediately after it enters the passage, the pressure side-leg vortex is driven by the blade-to-blade pressure gradient and convected toward the suction side, meeting the surface near the minimum pressure point. This forms the well-known "passage vortex" which represents one of the most dominant features of the secondary flow and a key factor responsible for the overall secondary loss. Having reached the suction surface, the passage vortex and the suction-leg vortex roll up altogether from the endwall, and the size of this combined vortex increases toward the blade trailing edge. An increase in vortex size on the passage exit plane generally leads to a greater secondary loss. With this underlying notion in mind, an effective means for reducing the secondary loss must be capable of suppressing the growth of passage vortex.

MEANS FOR SECONDARY LOSS REDUCTION

The ways to reduce secondary loss can be classified into two different categories: active reduction and passive reduction. The former typically involves boundary layer blown off and/or sucked off, and it requires additional flow movers, which may complicate the system and induce other undesirable loss (e.g. coolant loss). Hence the present study focuses exclusively on passive

loss reduction techniques. A literature review reveals that methods for passive reduction include (1) blade endwall fillet, (2) blade leaning, (3) boundary layer fences or grooves.

Blade Endwall Fillet

Implementing a fillet at the junction between endwall and blade suction side is to temper the corner sharpness so as to form a rounded corner in the region. The resulting effect is a weakened suction-side leg vortex (horseshoe vortex), especially in the leading section of a blade passage. Therefore, its reduction mechanism lies primarily on reducing the turbulent transport and frictional loss near the endwall and, on the other hand, has little effect on the dominance of passage vortex originated from the pressure side of the neighboring blade. The reduction of turbulence transport has recently been confirmed by Chyu (1990) in a thermal study on cylinders with endwall fillets.

Based on his theoretical analysis, Debruge (1980) has posed several interesting features concerning the influence of fillet geometry on compressor blade rows. He has pointed out that an effective fillet can induce a boundary layer with thinner displacement thickness near the corner junction, which generally implies a lower frictional loss. However, the interference between the boundary layers from the blade sidewall and endwall in actual blade configurations often presents severe limitation to yield a rigorous prediction near the corner region. The conventional two-dimensional, thin-layer approximation appears to be invalid for this case as the transport characteristics in both streamwise and cross-stream directions are comparable. The boundary layer is clearly three-dimensional in nature. In addition, implementing different sizes of fillet along the chordwise direction, which varies in compliance with the thickness of local boundary layer, may be desirable for an effective loss reduction. Most of the assessments aforementioned, while fundamentally sensible, still lack experimental confirmation, especially for actual turbine configurations. This undoubtedly is necessary for STME LOx turbine where blade design involves strong turning. The effects of fillet can become secondary as the turn-induced flow separation likely prevails in the region.

Blade Leaning

One of the major effects for using leaned (bowed) blades is to re-structure the radial pressure gradient near the lower corner of the suction surface. Figure 2 displays a schematic view of curvilinearly lean blades, which has an essential feature that the angle between the suction surface and the endwall must be dihedral. From the standpoint of radial momentum balance, such an arrangement can establish a negative radial pressure gradient along the suction surface. Hence the fluid particles with low momentum originally residing in the corner of blade/endwall junction will migrate toward mainstream. By continuity, this region will be replenished by fluid with higher momentum from mainstream. This overall reduces boundary layer separation or vortex roll-up from the lower corner of suction surface.

According to studies by Hubner (1985) and Wang et al. (1987, 1988), implementing leaned blades usually results in a more uniform radial pressure distribution at the passage exit plane as compared to the straight blades. This, in fact, is considered to be the most important mechanism for secondary loss reduction with leaned blade, especially for multiple stage turbine. A uniform outlet flow condition from the upstream stage generally enhances the stage performance downstream. It also alleviates the loss involving flow unsteadiness. Because of rotating stress consideration, leaned blades are more favorably used in the stator rather than in the rotor. Caution must be taken to avoid any blade-leaning induced deviation from the designed turbine loading characteristics.

Boundary Layer Fences or Grooves

Using fences for secondary loss reduction consists of two different approaches: (1) fences on blade, and (2) fences on endwall. For the former, two fences, both conforming the blade chordwise profile, are mounted on the suction surface, one located slightly away from the endwall and the other is near the tip. An effective blade fence can suppress the growth of boundary layer and prevent significant vortex roll up near the suction surface. With this concept in mind, the fence size should be in the order of boundary layer thickness. According to the data shown in studies by Prumer (1972) and Gallus and Kummel (1977), the local loss in the vicinity of fences is generally greater than that of a plain blade, but this is offset by considerable loss reduction in the section across mid-span. In a similar context, Gallus and Kummel (1977) also evaluated the effectiveness of grooves cut on the blade surface rather than mounting fences. Their data have suggested that grooves generally perform better than fences; however, this trend may be limited to the specific turbine and operating conditions tested.

Attaching fences on the endwall is a viable technique which presents direct blockage to the movement of passage vortex. Figure 3 shows a configuration of a fence placed in the mid-pitch between adjacent blades. With this geometry, Kawai et al. (1989) has reported that a fence with its height approximately $1/3$ of inlet boundary layer thickness is the most effective for control of secondary flow and associated loss. Compared to the case without fence, this optimal condition can reduce the secondary loss by nearly 22%. However, velocity mappings measured at the blade exit plane reveal that the secondary flow structure is very sensitive to the fence height and pitchwise location. This implies that such an optimal condition may vary with differences in turbine design and operating conditions. In an earlier study, Prumer (1972) has used multiple fences to expand the range of effectiveness; nevertheless redundant fences may introduce additional endwall loss.

CONCLUDING REMARKS

It is conceivable that adopting one or several of the methods aforementioned can effectively reduce the secondary loss in the future STME LOx turbine. The most effective approach appears to be using leaning blades for the stator and endwall fences for the rotor. As a research initiative for turbine loss reduction undertaken by the Consortium Turbine Team at MSFC, this advanced concept will be investigated rigorously using numerical modeling. This will be followed by actual testings, possibly conducted at Technology Turbine Rig (TTR) presently being developed at MSFC. Knowledge gained from this research will not only benefit space shuttle turbine performance in the future, but will also improve fundamental understanding in controlling secondary loss for other turbine engines.

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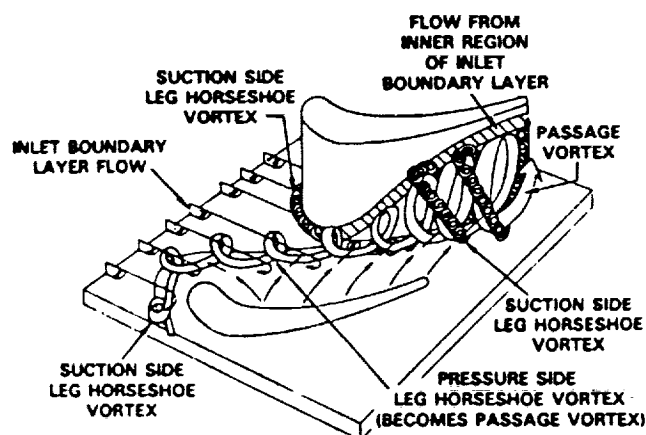


Figure 1. Secondary Flow

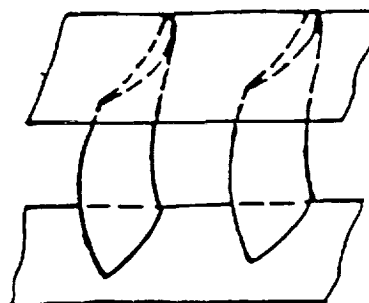


Figure 2. Curvilinearly Leaned Blade

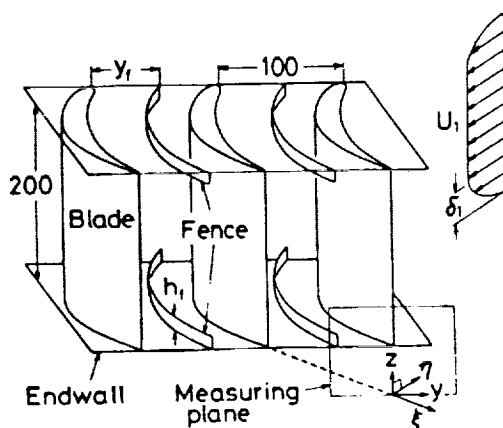


Figure 3. Endwall Fences